Improving File System Usability, Performance and Reliability with Magnetic RAM

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What is Magnetic RAM?

- Magnetic RAM (MRAM) is
  - Random access: speed comparable to DRAM
  - Non-volatile
- MRAM is byte-accessible
  - No need to read or write full blocks
- MRAM doesn't suffer wear
  - No need for wear-leveling
  - No limit on number of writes
- MRAM is now in production
  - Freescale has been making chips for over two months
- MRAM is (currently) expensive
  - Eventually cost comparable to DRAM
  - New product -> expensive!

Why file systems for MRAM?

- File systems traditionally use disk as non-volatile storage
  - Large blocks / transfer sizes
  - Expensive seeks
  - Metadata size relatively unimportant
- MRAM provides
  - Long-term storage
  - Byte-addressability with low seek time
  - High-speed access to complex metadata
- Problems:
  - Cost is a major issue (≥ DRAM)
  - File systems aren't designed to take advantage of MRAM
- What should a file system for MRAM look like?

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What should we keep in MRAM?

- Memory (non-volatile or otherwise) is expensive
  - Keep small items in it?
  - Keep recently used items in it?
- Large (data) transfers don't benefit as much from memory residence
  - Most transfers are large and sequential
  - Latency can be hidden with prefetching and writebehind
- Metadata is perfect for MRAM!
  - Small transfers (often a word or two)
  - Still very large: about 1% of total file system size
  - Reduce memory demands with new metadata structures and compression
  - Allows the construction of richer metadata structures that might require non-sequential accesses

Outline

- Introduction to MRAM for file systems

- LiFS: Linking File System
  - More effective searching and organization
  - Made possible by MRAM's speed

- Compressing metadata in MRAM
  - Making the most of a scarce resource

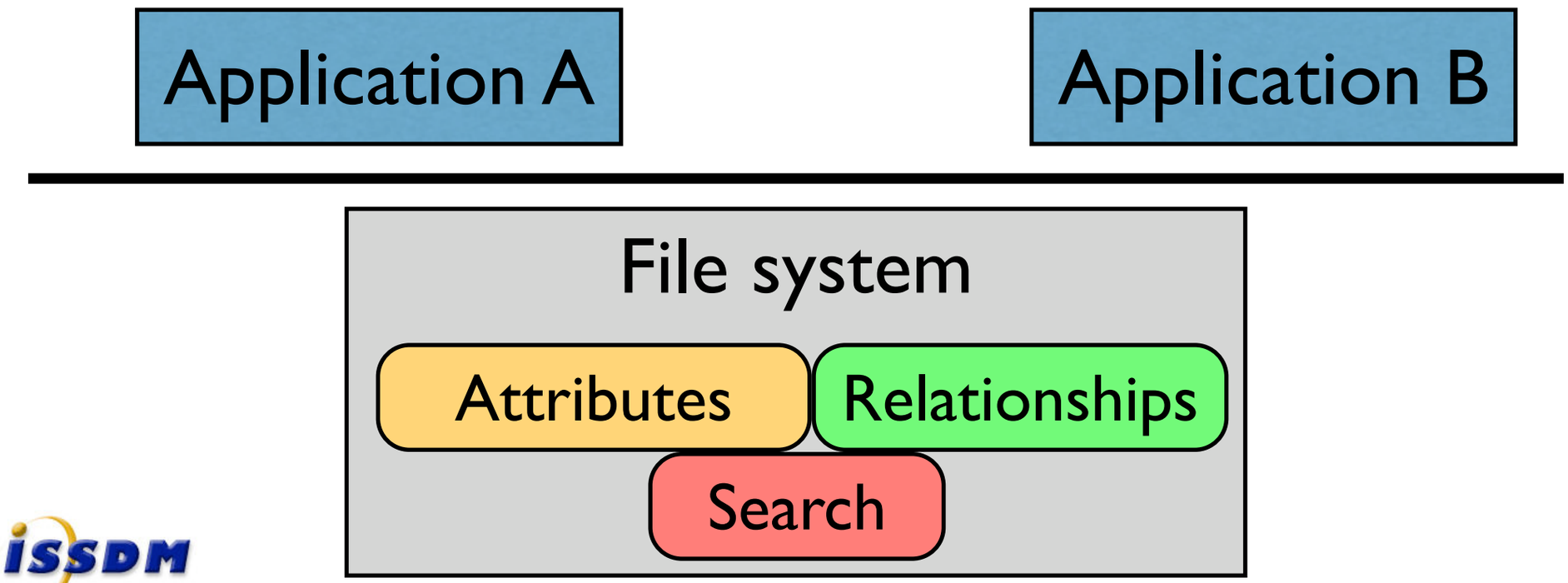
- MRAM reliability techniques
  - Making MRAM safe for file systems

The problem with metadata

- The number of files is dramatically increasing
  - Disk capacity is far larger
  - Applications like to use lots of files
- How can we organize them?
  - Directories?
    - Good model for few files, but not for billions!
    - Difficult for general directed graphs: files are typically in only one directory
  - Applications?
    - Many apps manage their own files
    - Works (somewhat) but makes sharing difficult

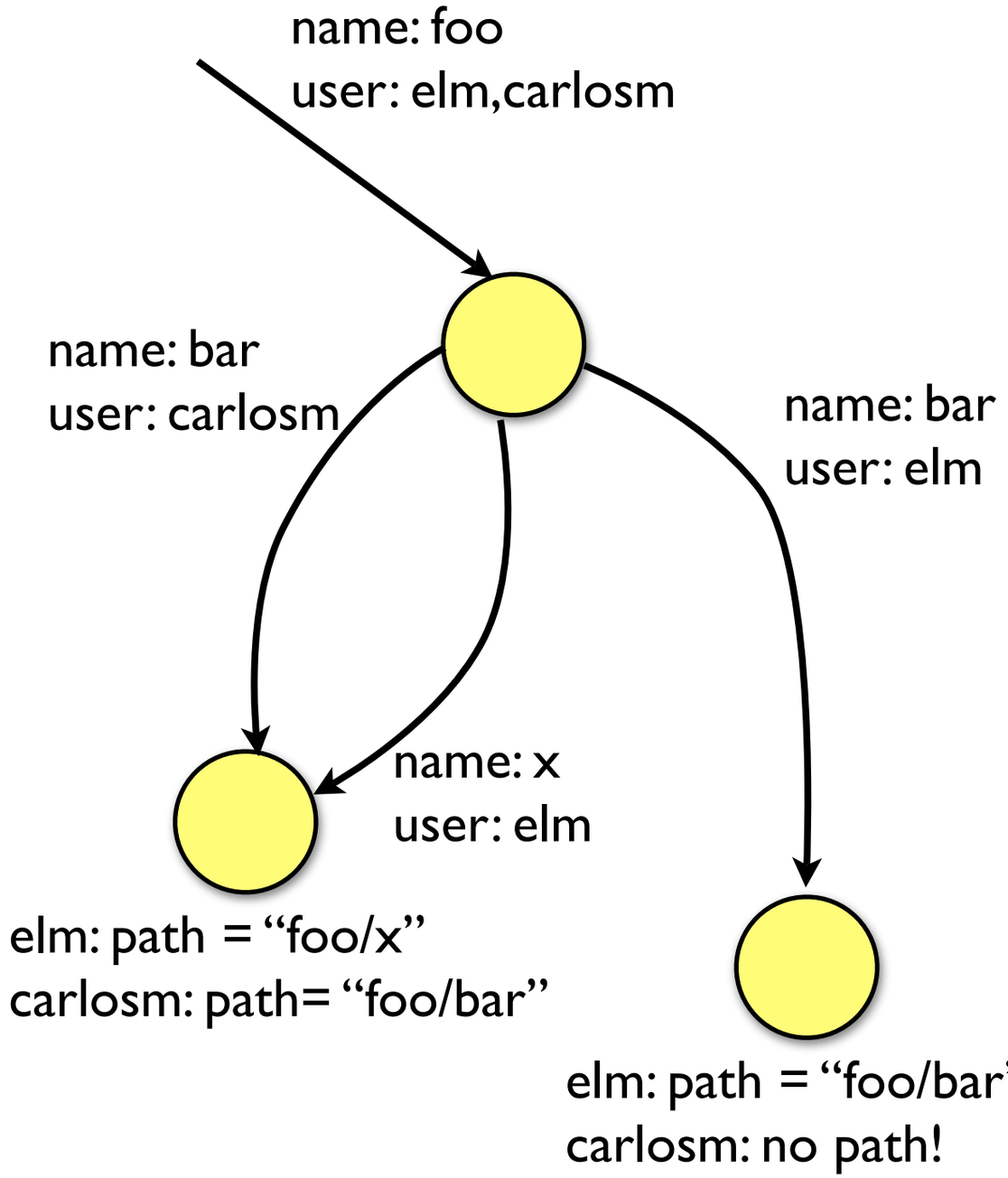
The solution: attributes & links

- Extend application approach into the file system
  - Provide primitives to manage the relationships
  - Allow multiple apps to use the same files and links
- Sharing is easy
  - File system maintains the relationships
- Searching is now possible…



MRAM makes this possible

- Directed links between files to show relationships
- Links have attributes
  - Express the type of relationship between the files
  - Describe the link itself
- Lots of links means lots of "seeks"
  - MRAM makes this fast
- Links are small
  - MRAM has low latency
- Searching can be slow
  - Keep the indices in MRAM



New system calls

System Call	Function
`rellink`	Create relational link
`rmlink`	Remove relational link
`setlinkattr`	Set attributes on link
`openlinkset`	Return handle to all the links from a file
`readlinkset`	Get name and attributes of next link in the set

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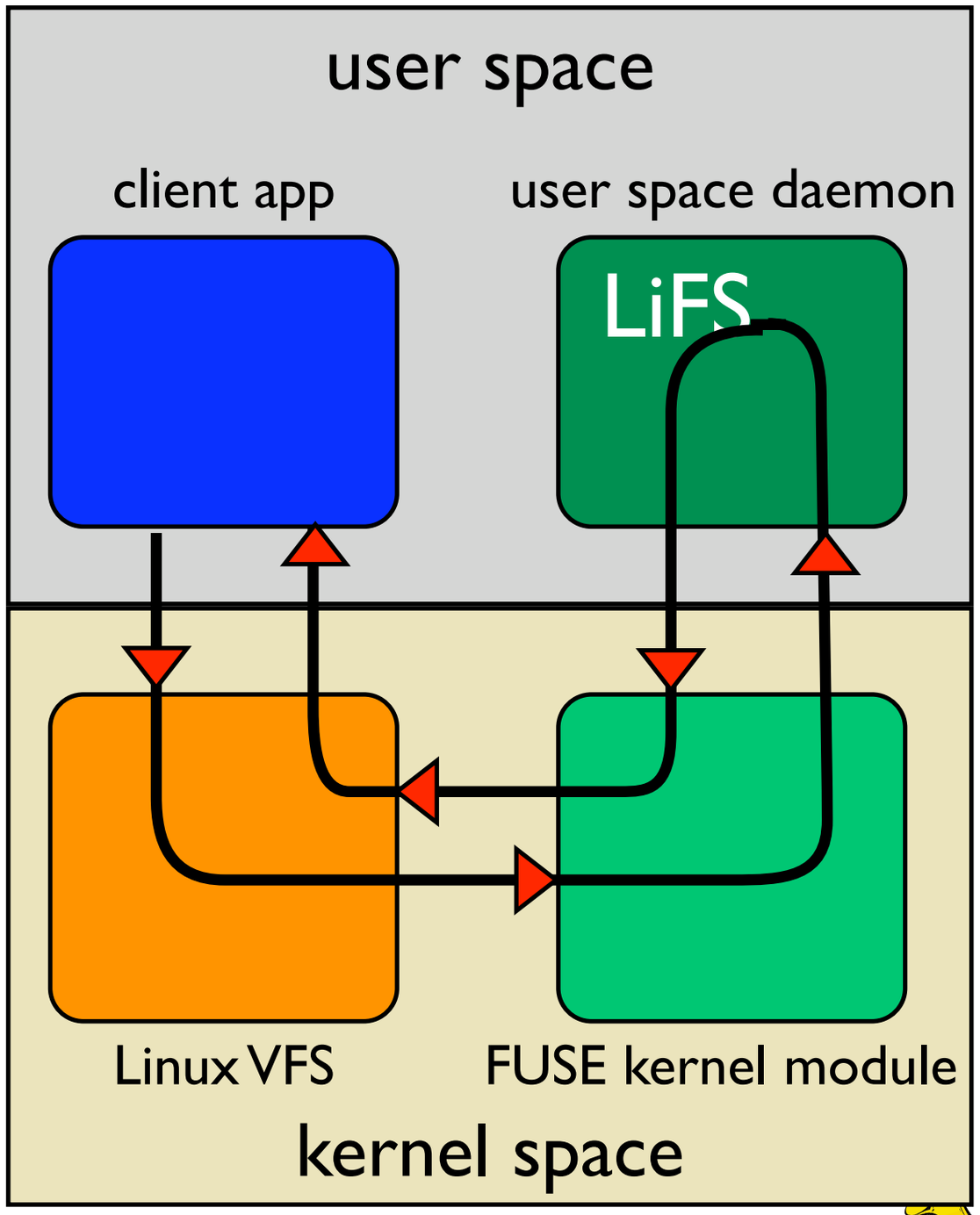
Implementation

- FUSE: maps VFS calls back into user space
- MRAM: system memory locked into DRAM
  - Not yet using MRAM...
- Custom MRAM allocator with fixed-size pools
  - Efficient to allocate and free small objects
- Optimizations
  - String table
  - Full path name cache



Evaluation

- Metrics
  - Traditional FS operations: compare to other file systems
  - New FS operations: scalability
  - FUSE overhead
- Experimental setup
  - Sun workstation running Linux 2.6.9-ac11
  - AMD Opteron 150 @ 2.4 GHz
  - 1 GB DRAM

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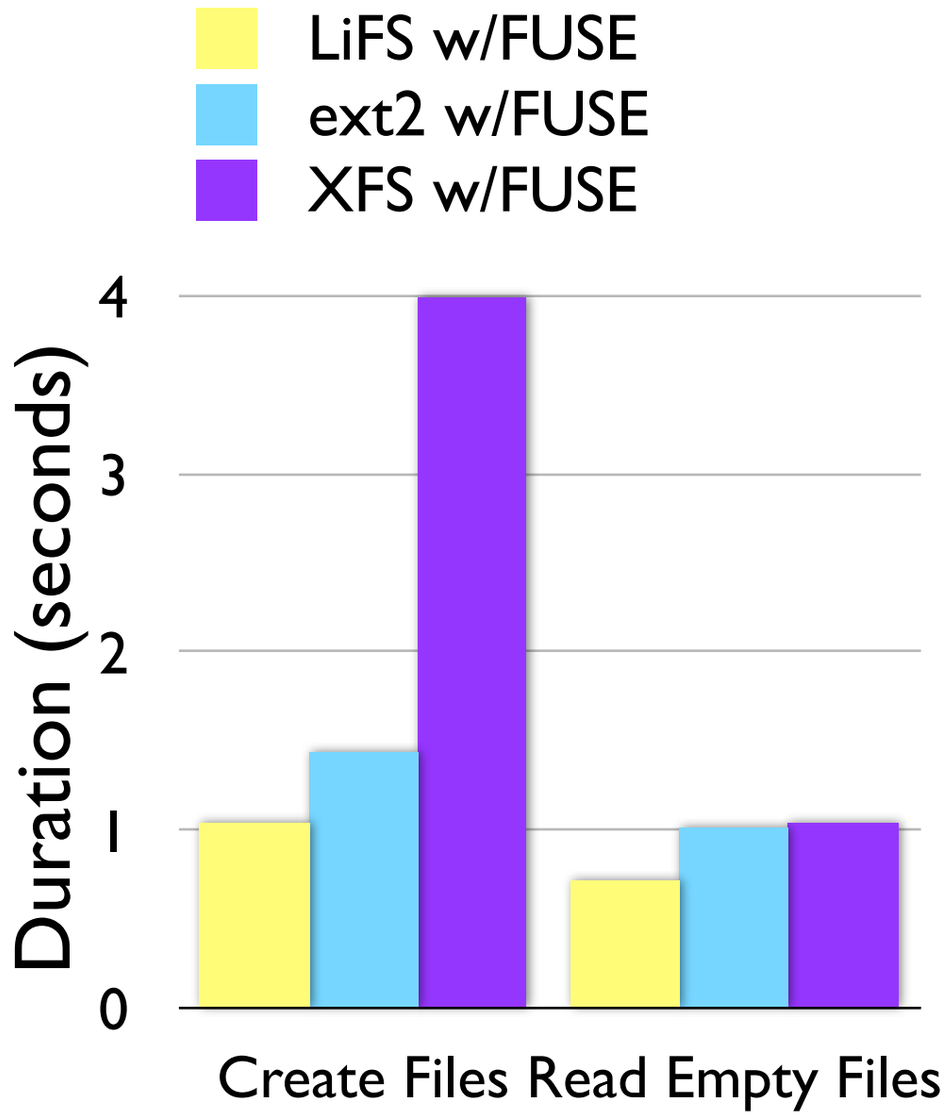
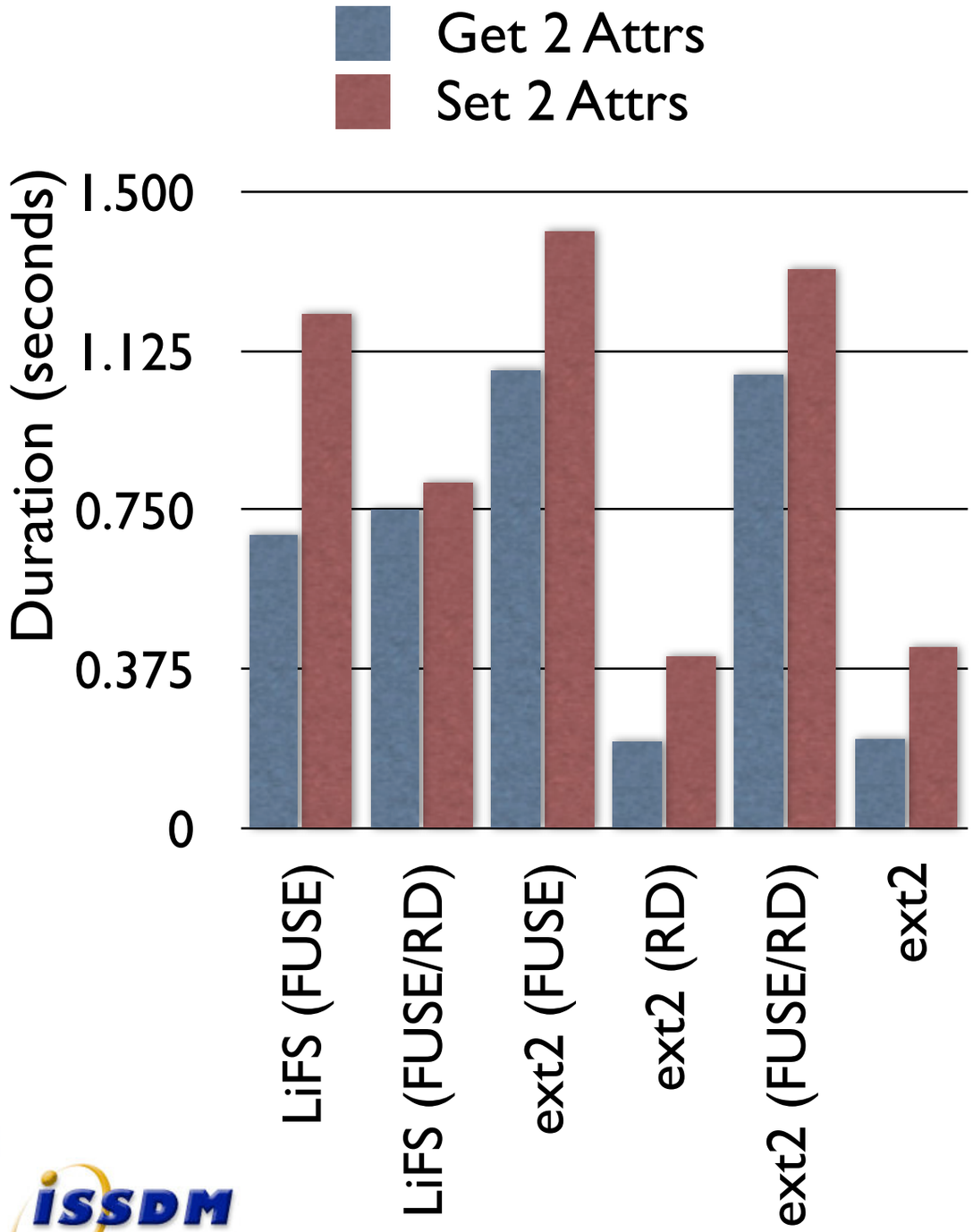
Performance: Files

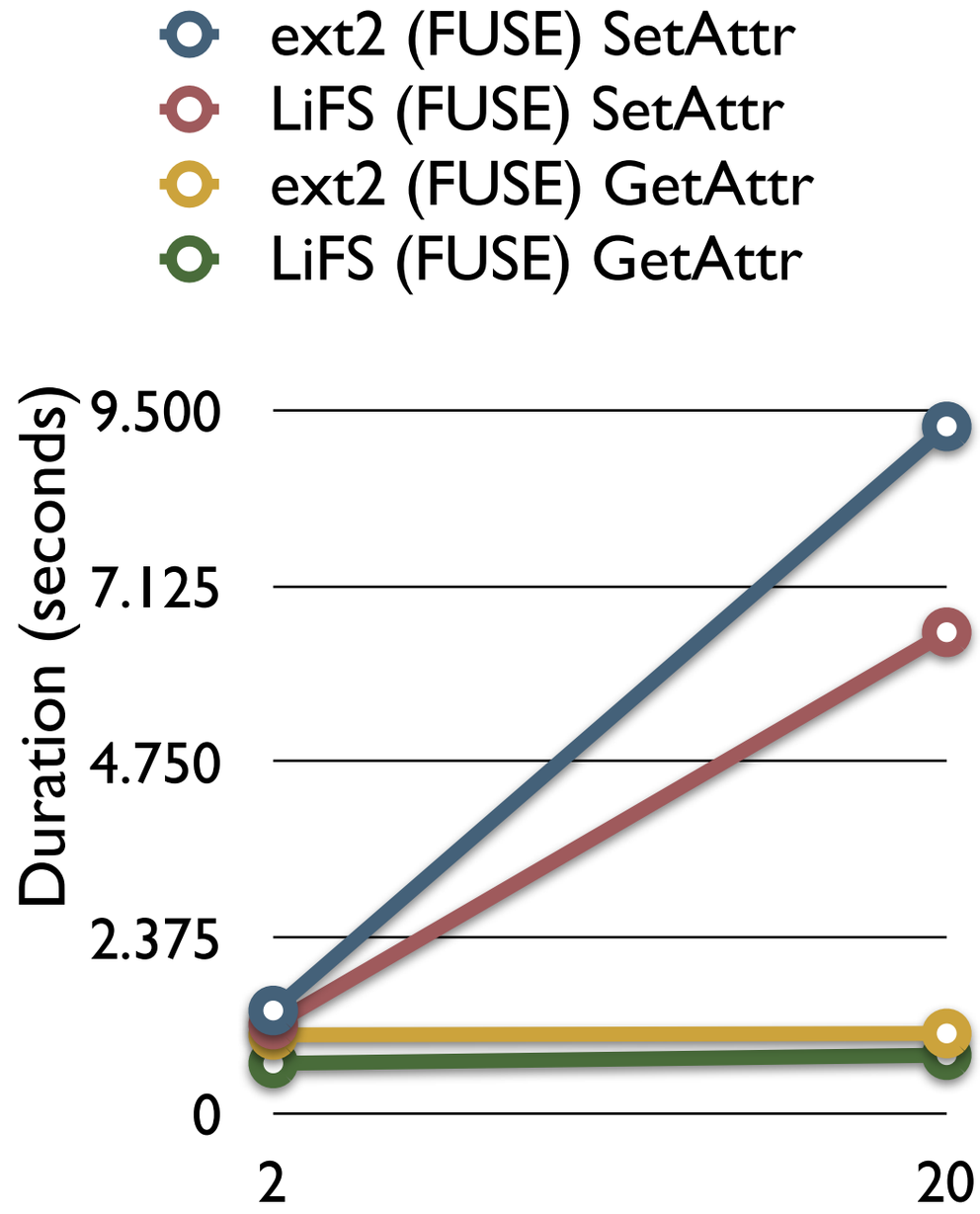
- Create a directory tree with empty files
  - 15620 files
- Read all of the files
- File systems are "fresh"

- LiFS is competitive

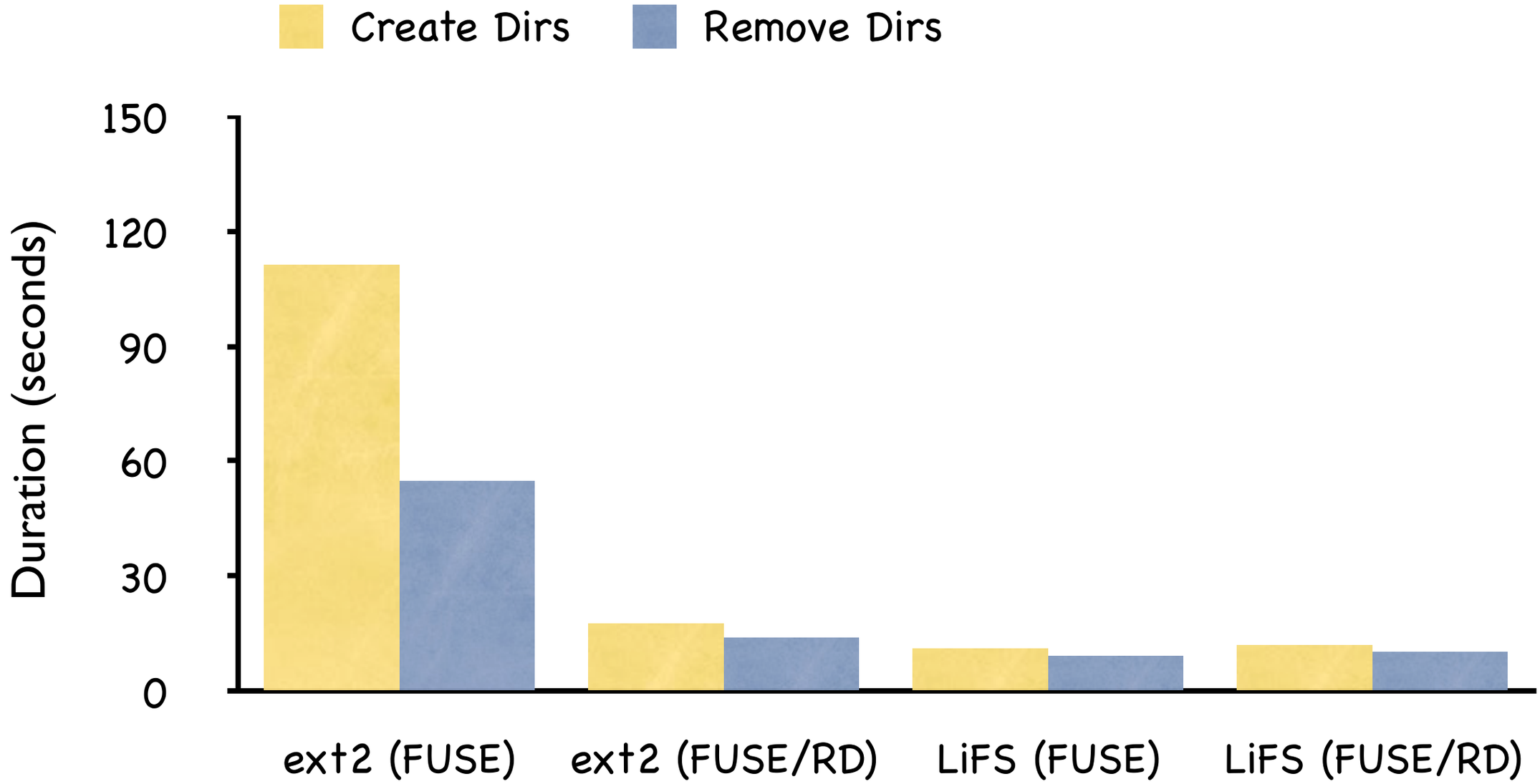


Performance: File Attributes





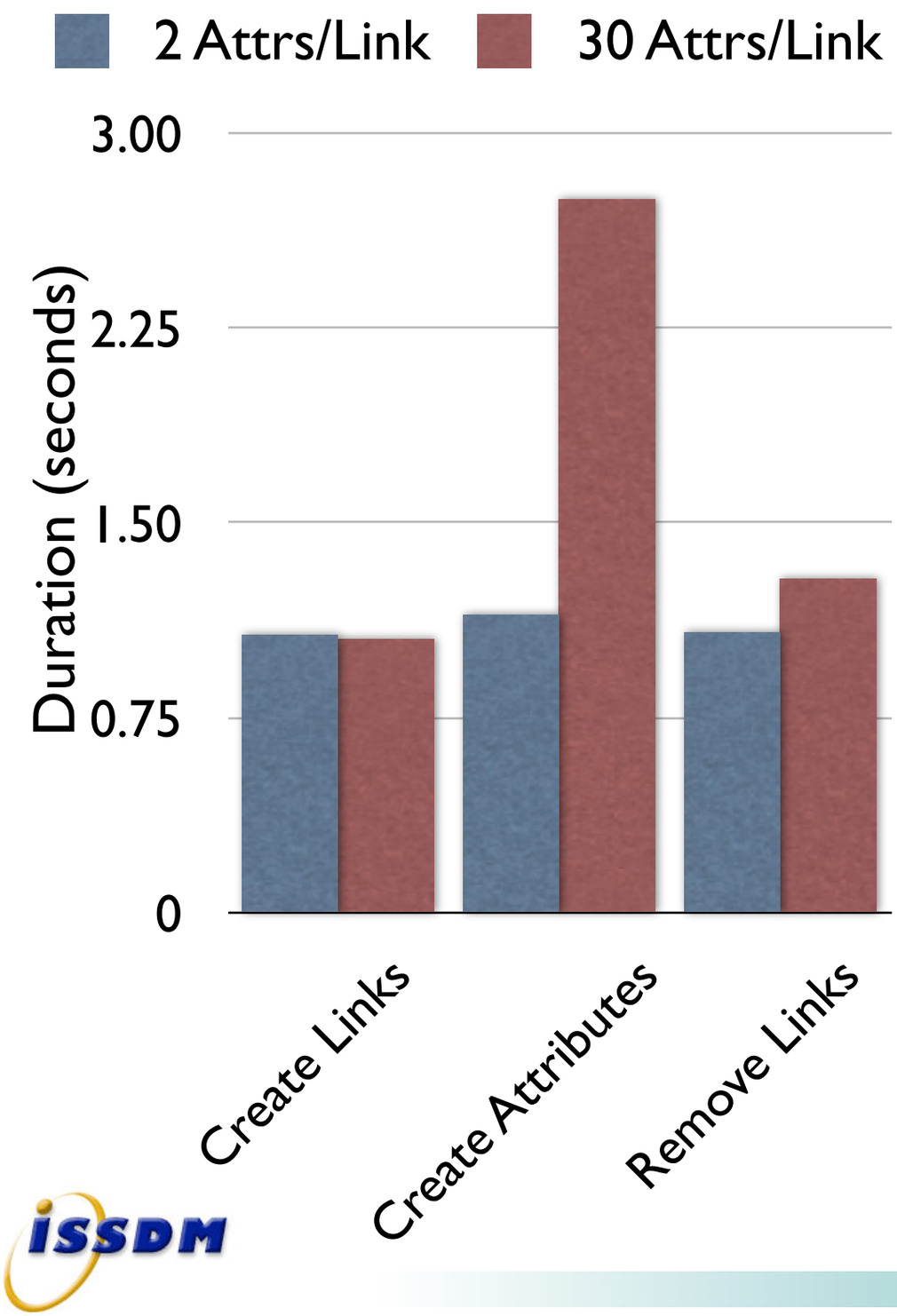
Create / Remove Directories



111,110 directories

LiFS outperforms ext2 with FUSE and RAM disk

Create / Delete LiFS Links



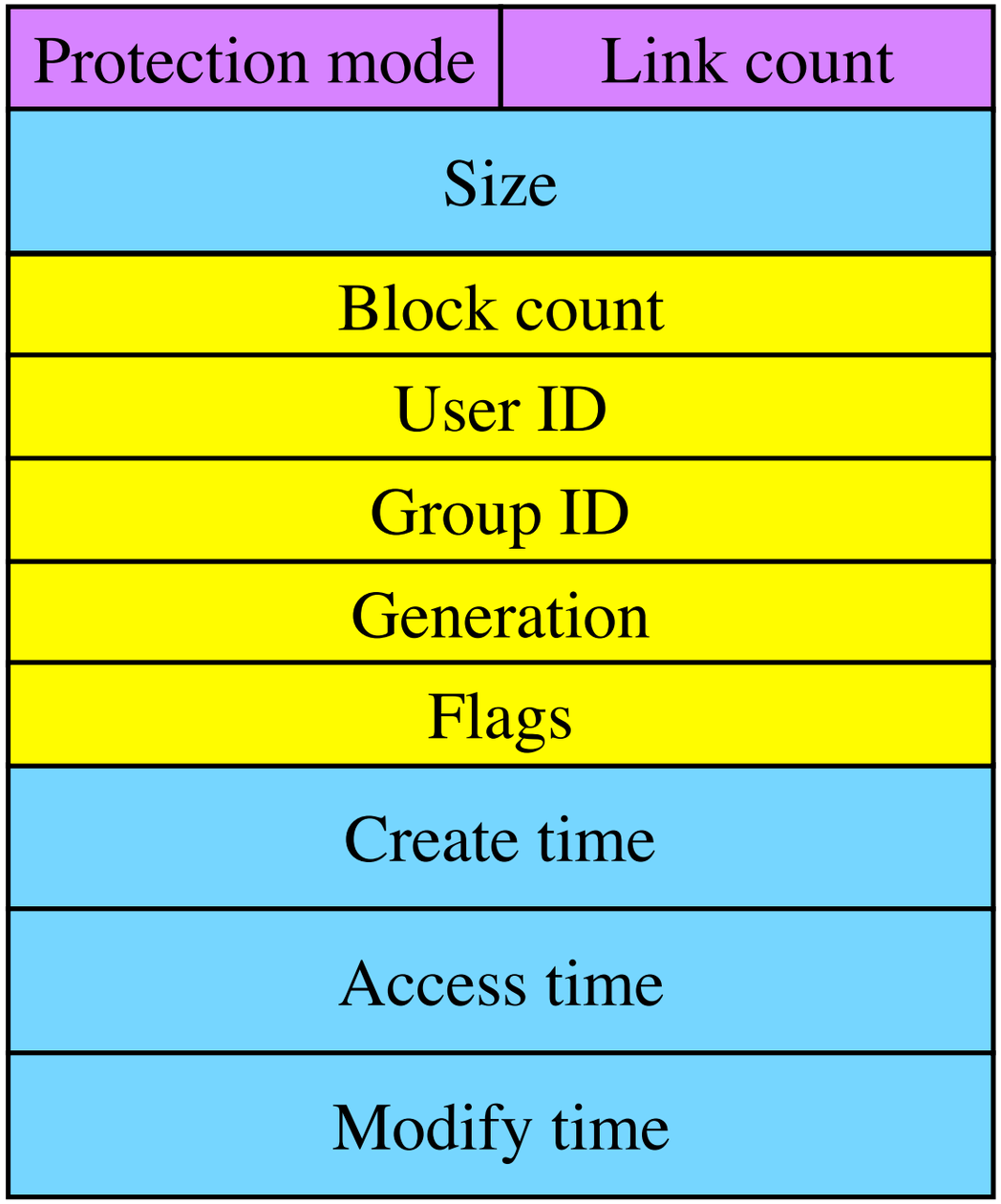
- Test on 15,620 files
- Processed 15,620 random links
- More attributes make link identification slower
  - Need to traverse structures to identify desired link

Compressing Metadata in MRAM

- LiFS promises lots of additional functionality, but…
- MRAM is expensive!
  - Currently, much more than DRAM
  - Eventually, costs drop to about DRAM costs
- Important to save space in MRAM if possible: compress metadata
  - Reduces MRAM requirements
  - May improve speed by reducing the amount of data moved
  - Byte-accessible MRAM makes this feasible

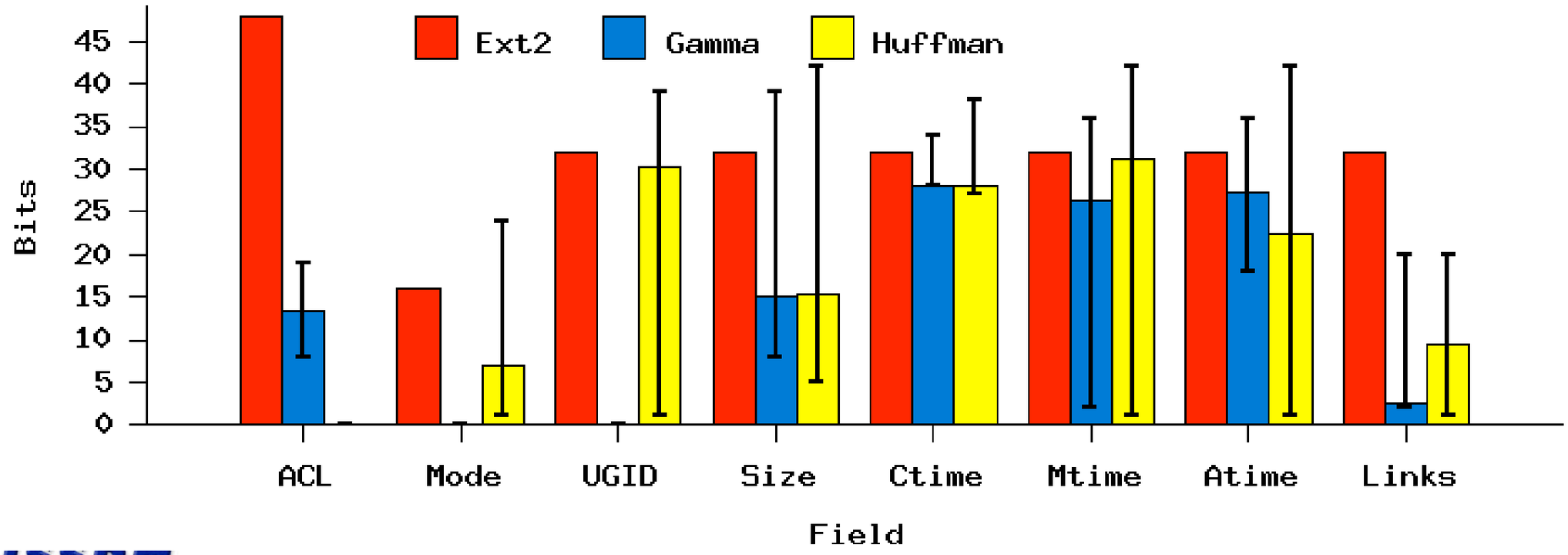
Metadata in Unix

- Metadata is stored in inodes
  - Timestamps
  - Ownership
  - File size
  - Link count
- Directories point to inodes
  - Inodes themselves don't contain names
- Total size is about 54 bytes
  - Times, size are 64 bit fields



Compressing metadata

- Most metadata is compressible
  - Integers have small values (link count, size)
  - Times can be expressed as offsets
  - Permissions can be table-based
- Compression is effective
  - 15–20 bytes per inode on typical file systems (factor of 2.5–3.5)
  - Inodes are variable-sized: compression rate varies
- Can this be used in a real file system?
- How does it affect performance?



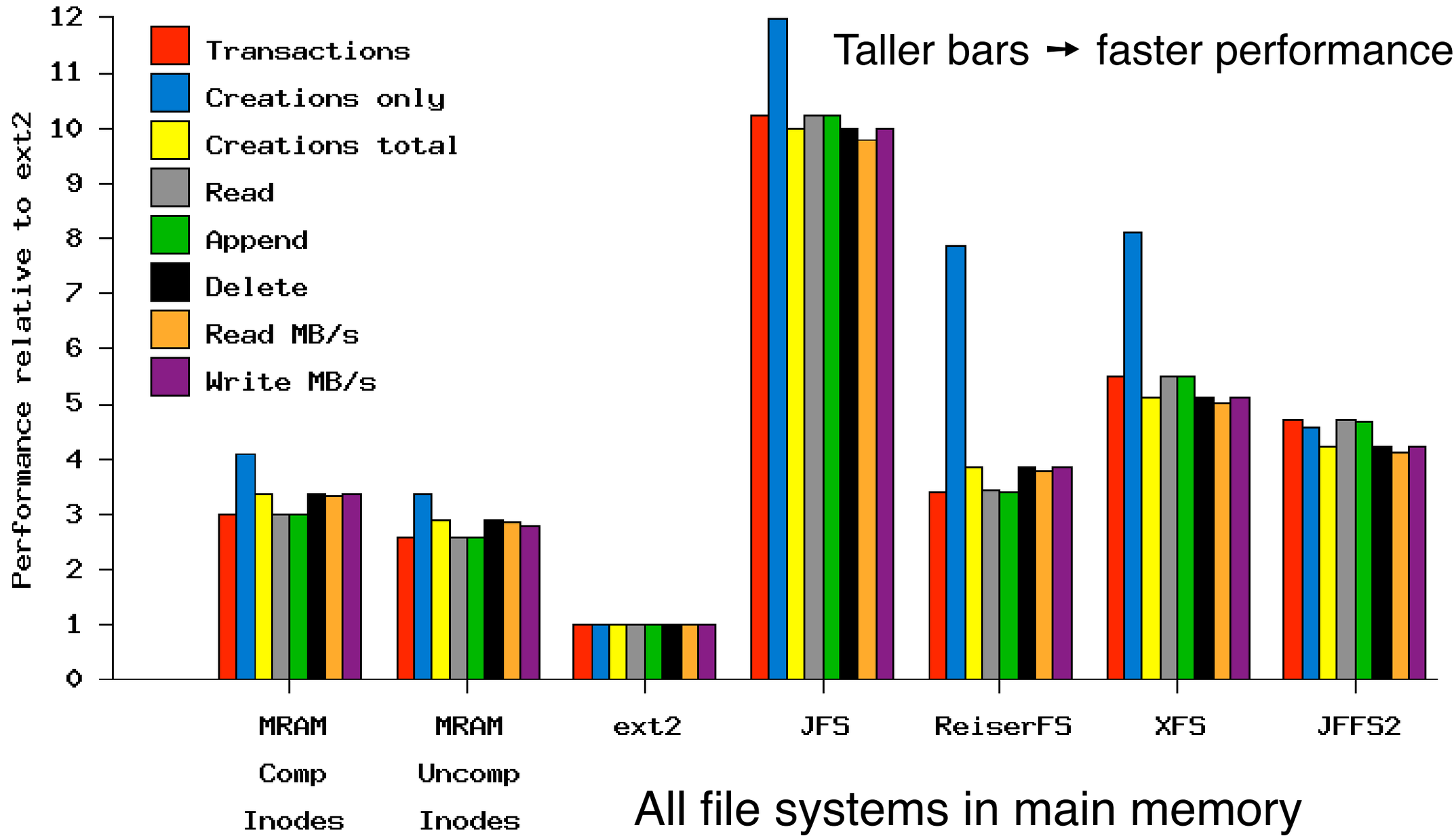
Inodes and file data

- Fields in the inode are gamma compressed
  - Small numbers compress very well
  - Timestamps are encoded as deltas from earliest time
- Permissions are table-based
  - Table contains all unique combinations of <*user ID*, *group ID*, *permissions*>
    - Most common combinations stored early in the table
  - Location in table of this inode's permissions is gamma-compressed
  - Table could easily be extended to handle ACLs…
- File data stored in compressed blocks
  - Linked list of block pointers
  - Random seeks not slow: pointer chasing is in RAM
  - Hybrid on-disk / MRAM-based system will need some minor changes

Separation of MRAM and DRAM

- Most memory-based file systems simply use the caching structures as "permanent" storage
  - Very fast: almost no copying
  - Inefficient: caches designed for very fast lookup at the cost of higher memory usage
  - Unsuitable for MRAM / DRAM systems
    - Must build the whole system from MRAM
    - No way to "start clean"
- MRAMFS explicitly copies from non-volatile memory to DRAM
  - Metadata and data copied back and forth
  - Can be slower for large operations
  - May be more reliable: fewer code points where permanent store is accessed and modified

Postmark benchmark results



All file systems in main memory
All file systems faster than disk-based

Postmark results

- All of the file systems run in-memory
  - Ext2 slowest by far: sequential directory handling
  - JFS very fast
  - MRAMFS comparable to ReiserFS
  - MRAMFS slightly slower than XFS, JFFS2
- All but JFFS2 are uncompressed
  - Memory usage higher by a factor of about 3
  - JFFS2 compresses blocks: not as efficient for inodes
- Compressed inodes faster in MRAMFS!
  - Less metadata copied: faster performance
  - Compression can provide speed increase by avoiding accesses to (relatively) slow DRAM

Compression reduces MRAM demand

- File systems will run much faster with non-volatile memory
  - Don't need to read metadata from disk
  - Don't write metadata back to disk
  - Fast access to parts of an inode
- Compression of metadata can reduce memory usage and thus cost
  - Factor of 2–3 or more
  - May save time, too: less data movement between (relatively) slow main memory and cache
- Alternate file structures can make efficient use of MRAM and other non-volatile memories
  - Relatively small allocation chunks
  - Simple, reliable file system design
  - No need for complex structures that may introduce bugs

Making MRAM file systems safe

- MRAM advantages
  - Fast metadata access
  - Richer metadata structures
  - Reduces sync and transfer overhead
  - File system log for fast recovery
  - Fast, on-line consistency checking
- MRAM disadvantages
  - Wild writes from buggy software
    - Potentially much less "control" than with disk-based file systems: no centralized I/O access routines
  - Bit flips on MRAM
- How can this corruption can be prevented?

Solution: Two-Level Approach

- Attack the problem on multiple levels
  - Guard against memory corruption due to OS mistakes
  - Check file system operations to make sure that they're correct

- Memory consistency
  - Page-level write protection
  - Error Correcting Codes (carefully chosen)
- File system consistency
  - Log/periodically check structure changes
  - On-line checks (log replay)

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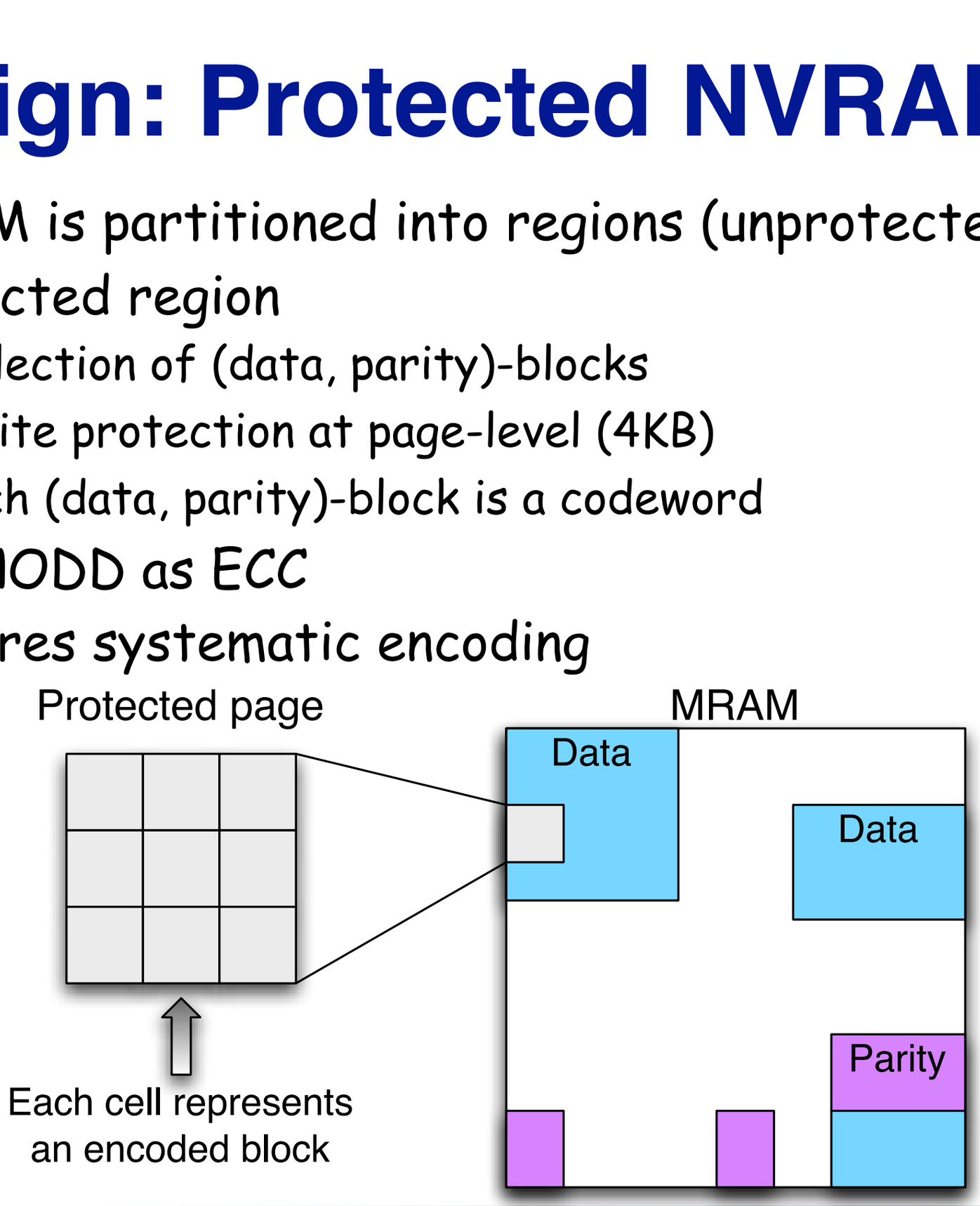
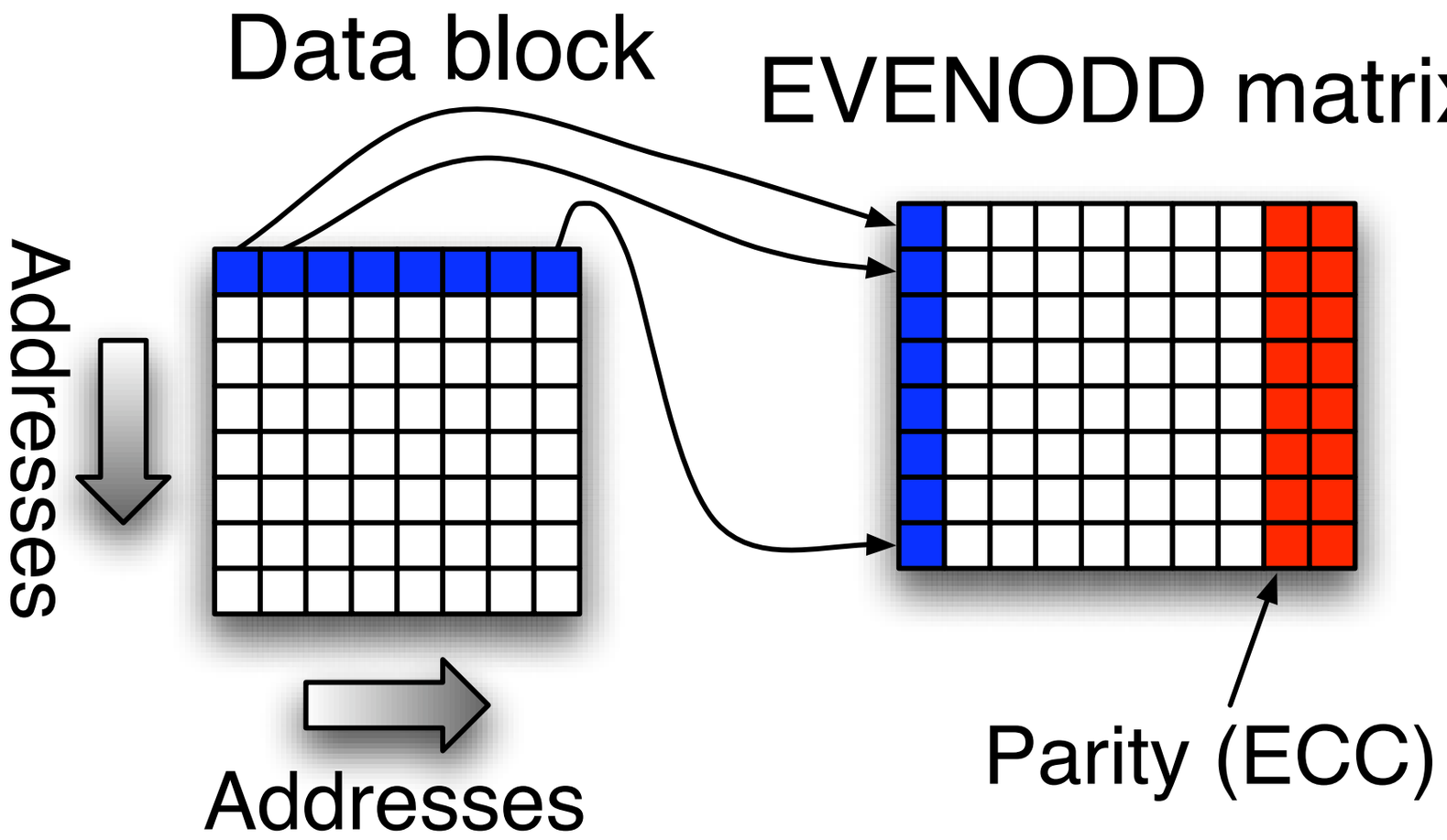
Design: Protected NVRAM

- MRAM is partitioned into regions (unprotected/protected)
- Protected region
  - Collection of (data, parity)-blocks
  - Write protection at page-level (4KB)
  - Each (data, parity)-block is a codeword
- EVENODD as ECC
- Requires systematic encoding



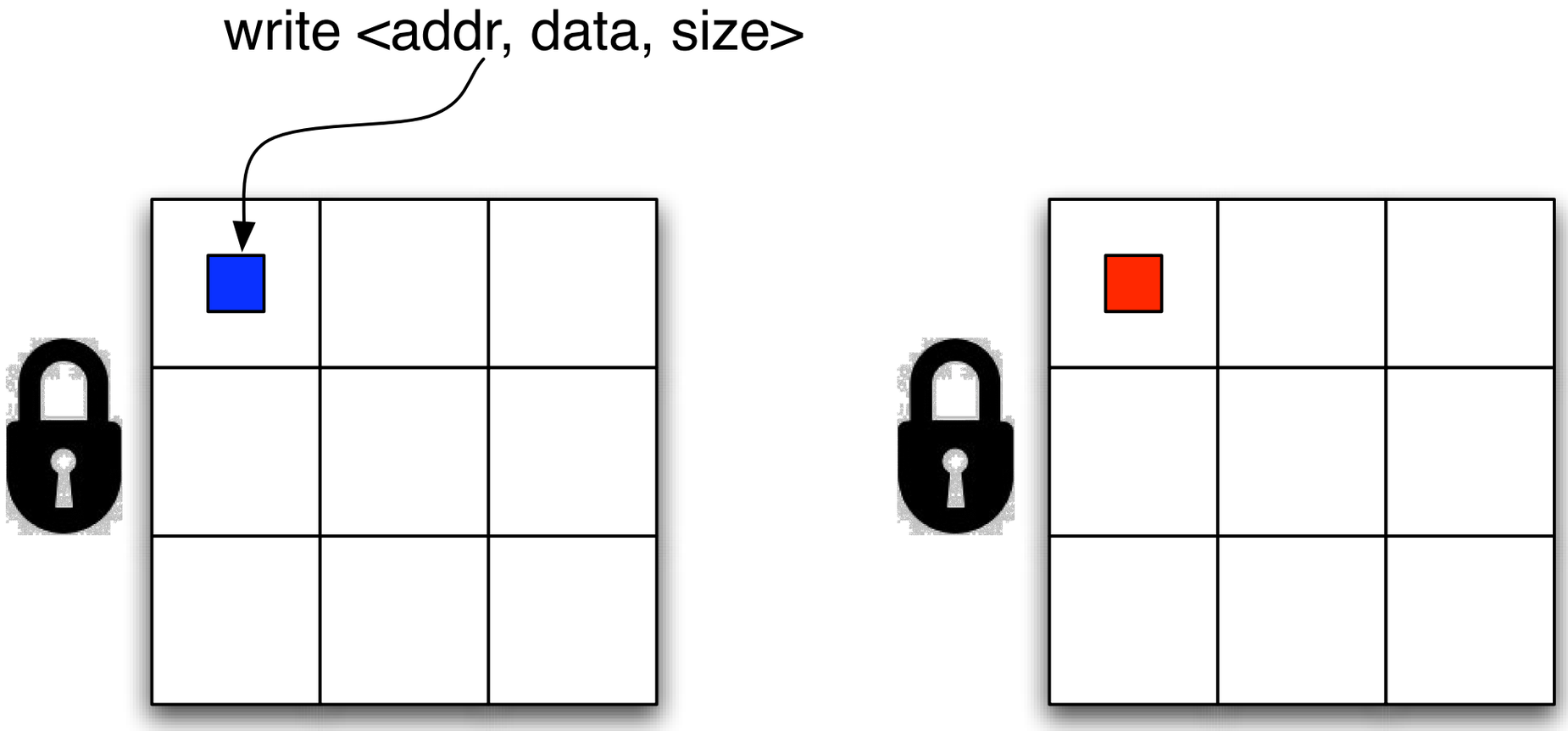
Design: Mapping Data to EVENODD

- Visualize the data block as a 1D array mapped to 2D array
- Can tolerate any one column error (bursts)



Write Algorithm: identify location

Step 1: Identify address and write size

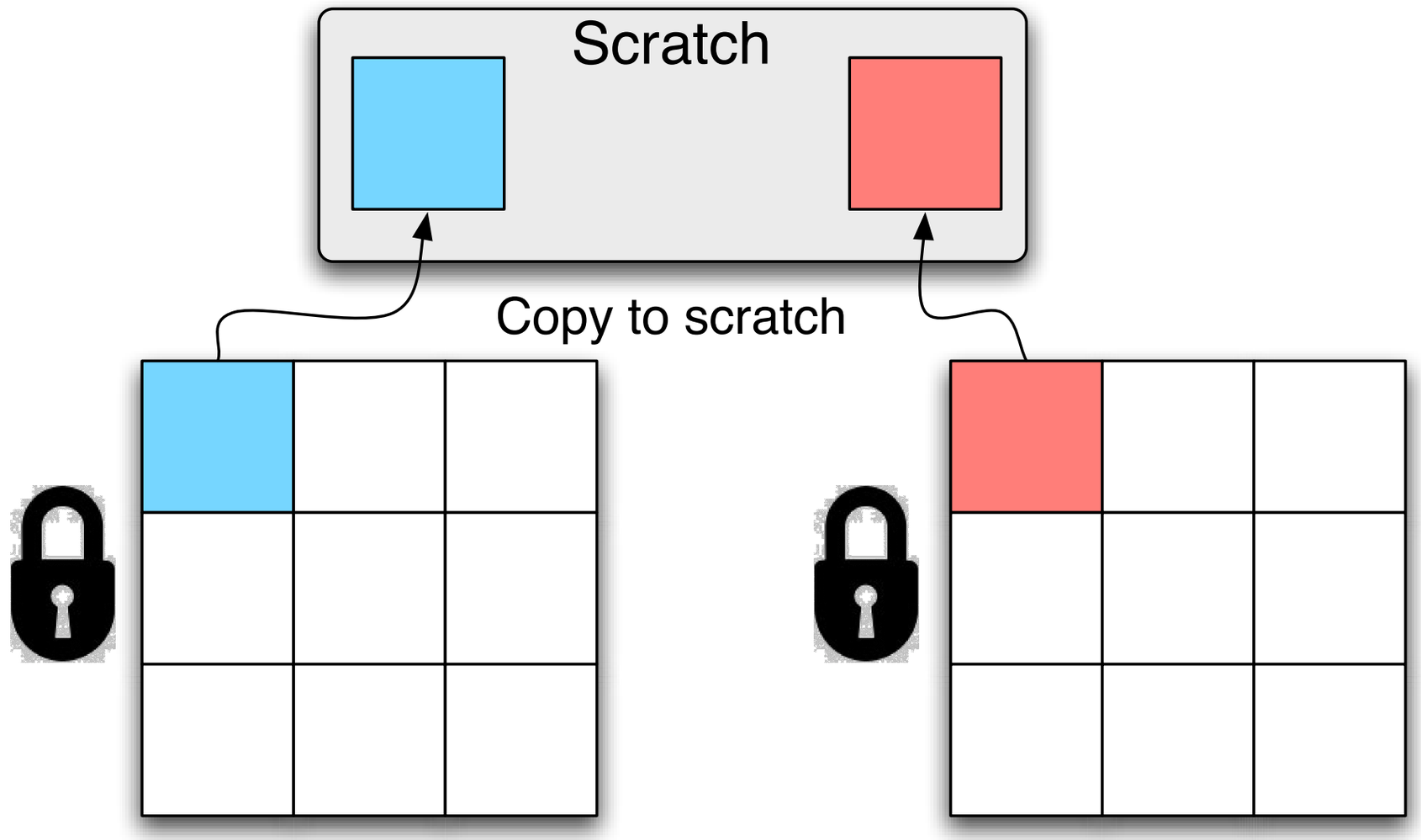


Data Page

Parity Page

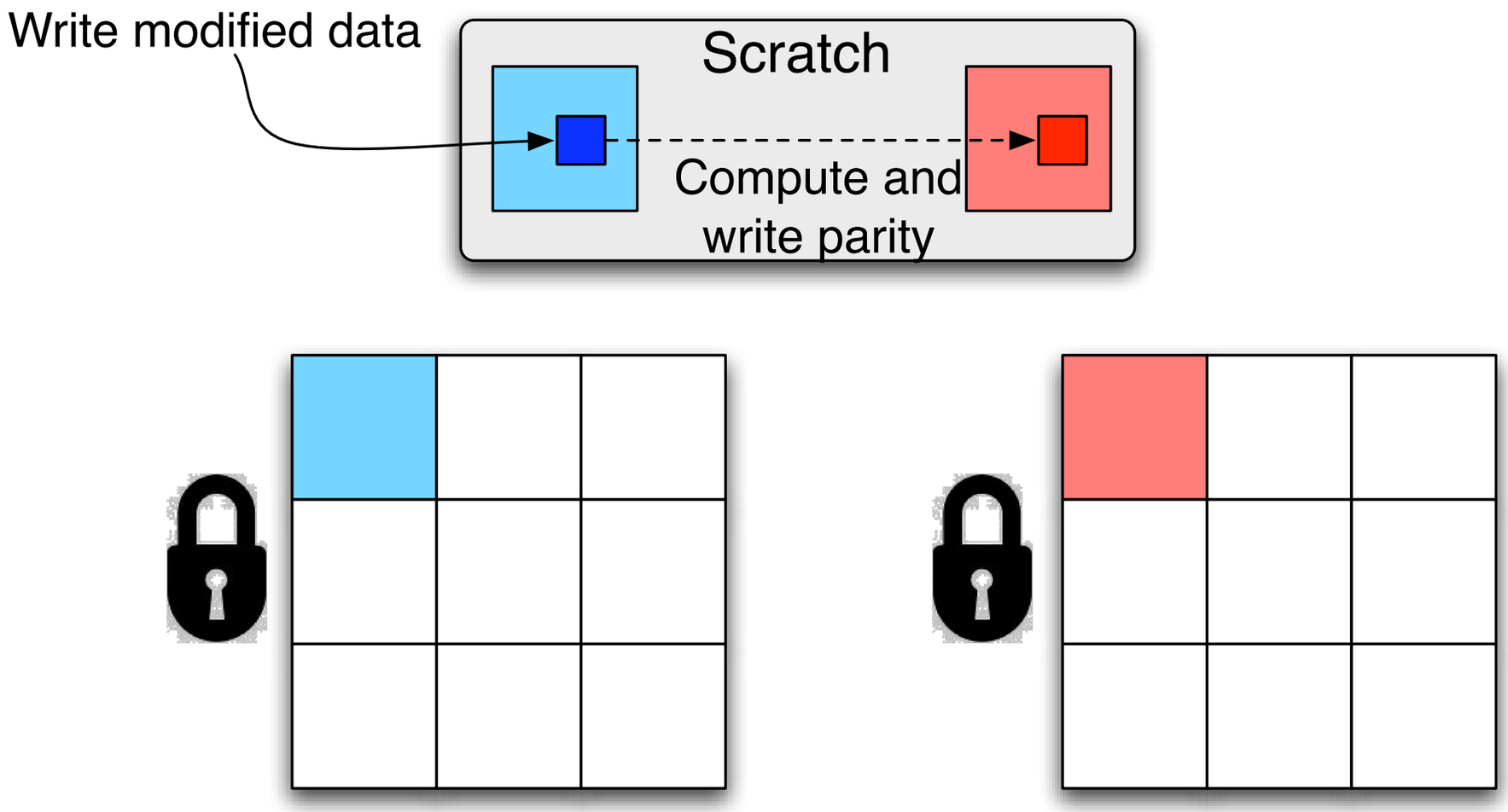
Write Algorithm: copy to scratch

Step 2: Copy corresponding data/parity sections out to "scratch"



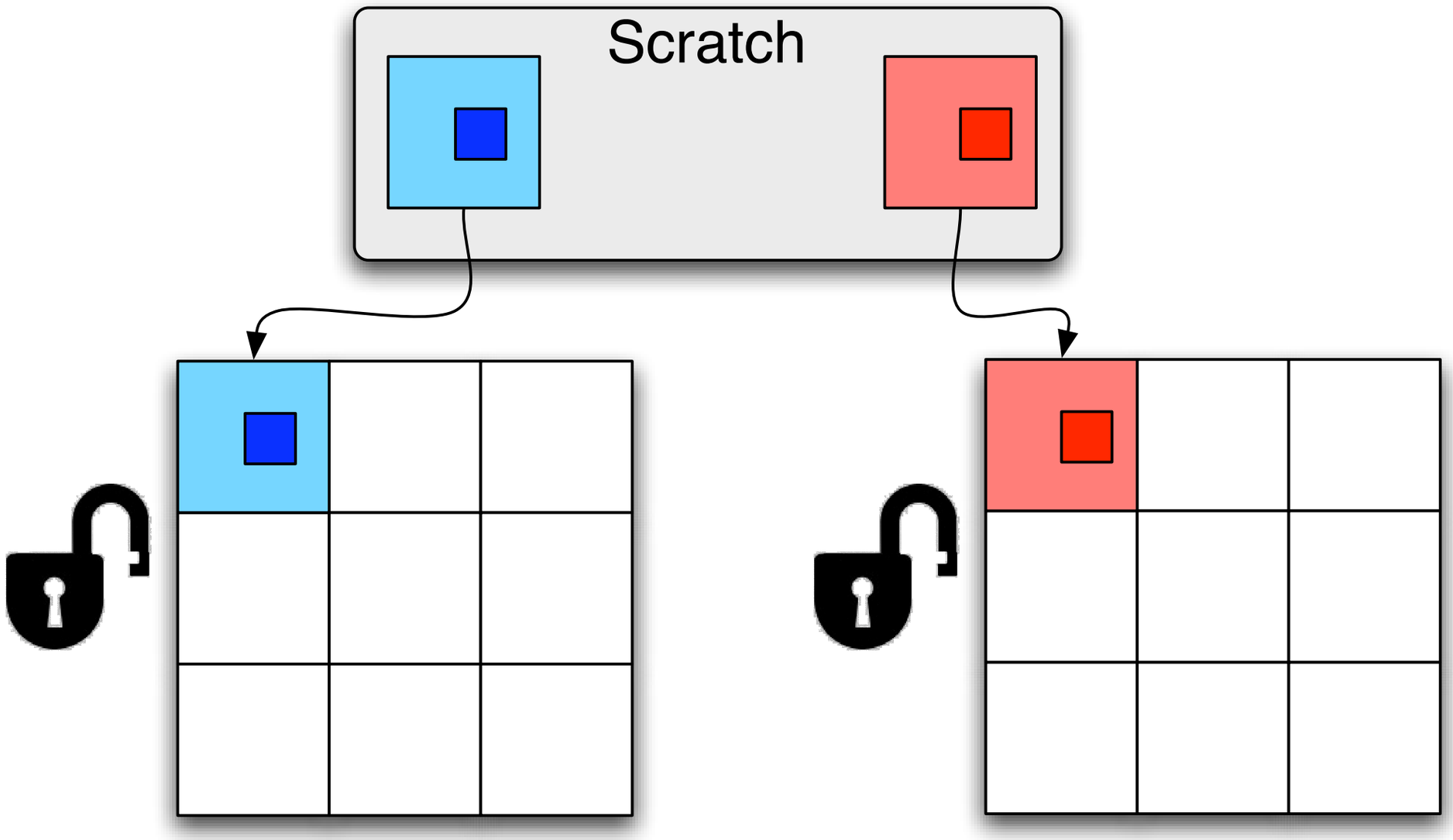
Write Algorithm: update in scratch area

Step 3: Write change in scratch region, compute parity



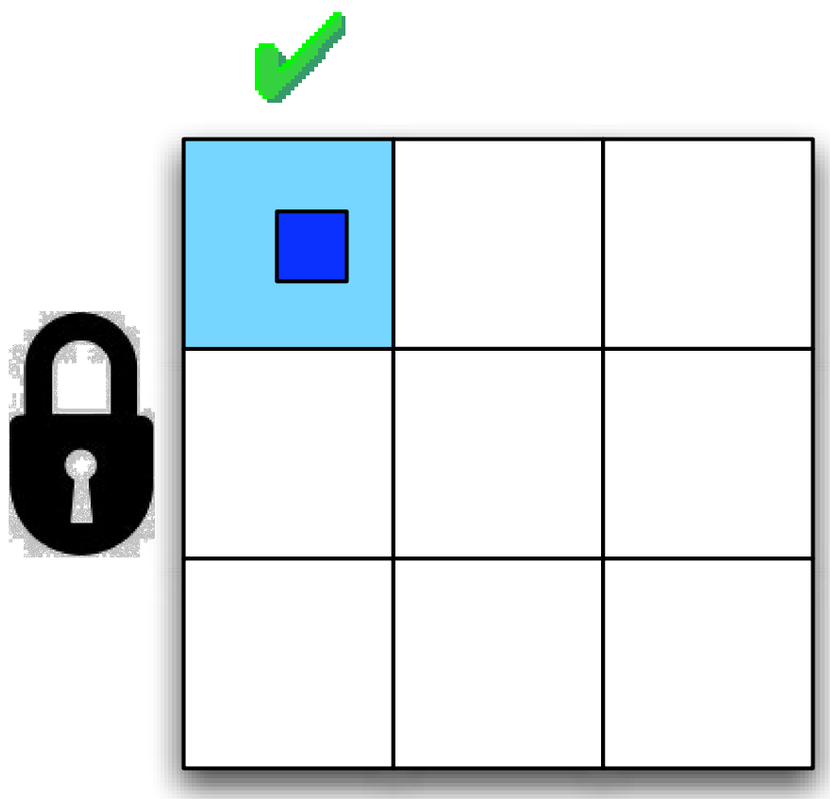
Write Algorithm: write back changes

Step 4: Unlock pages and write changes (vulnerable)

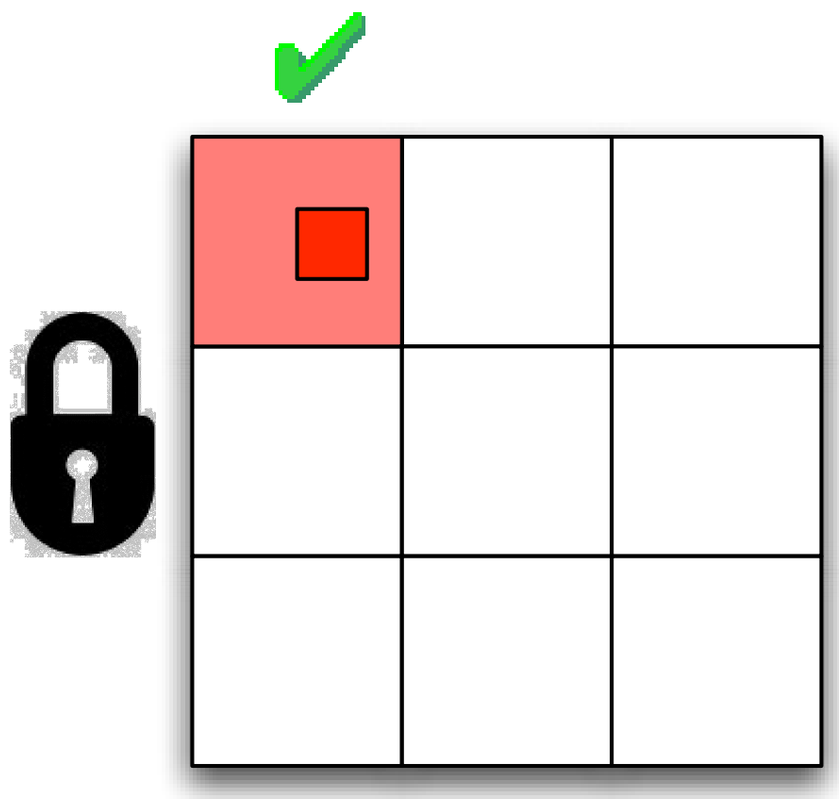


Write Algorithm: check writes

Step 5: Lock pages and check for errors



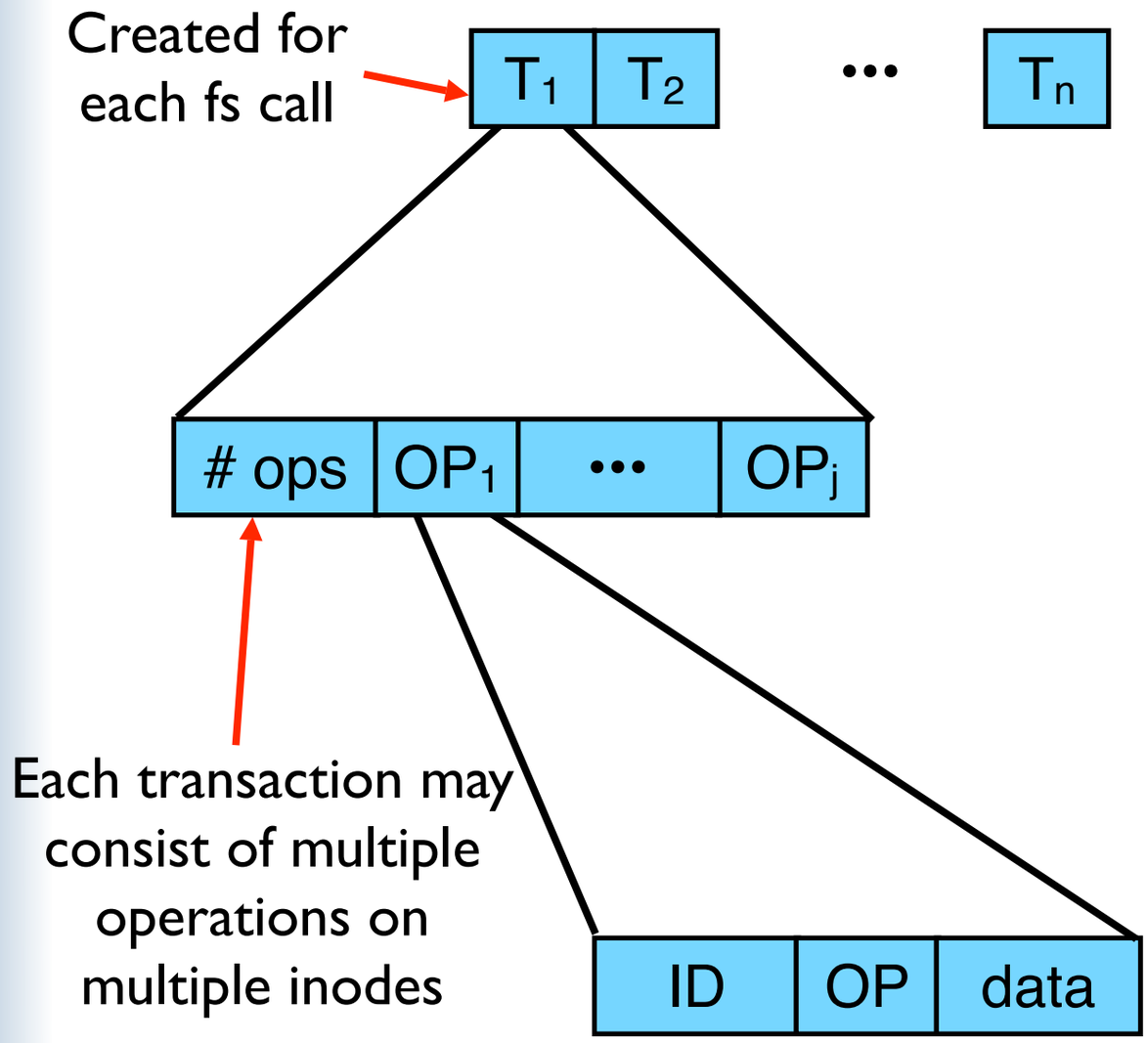
Data Page



Parity Page

Design — Transaction Log

Transaction Log



State Table

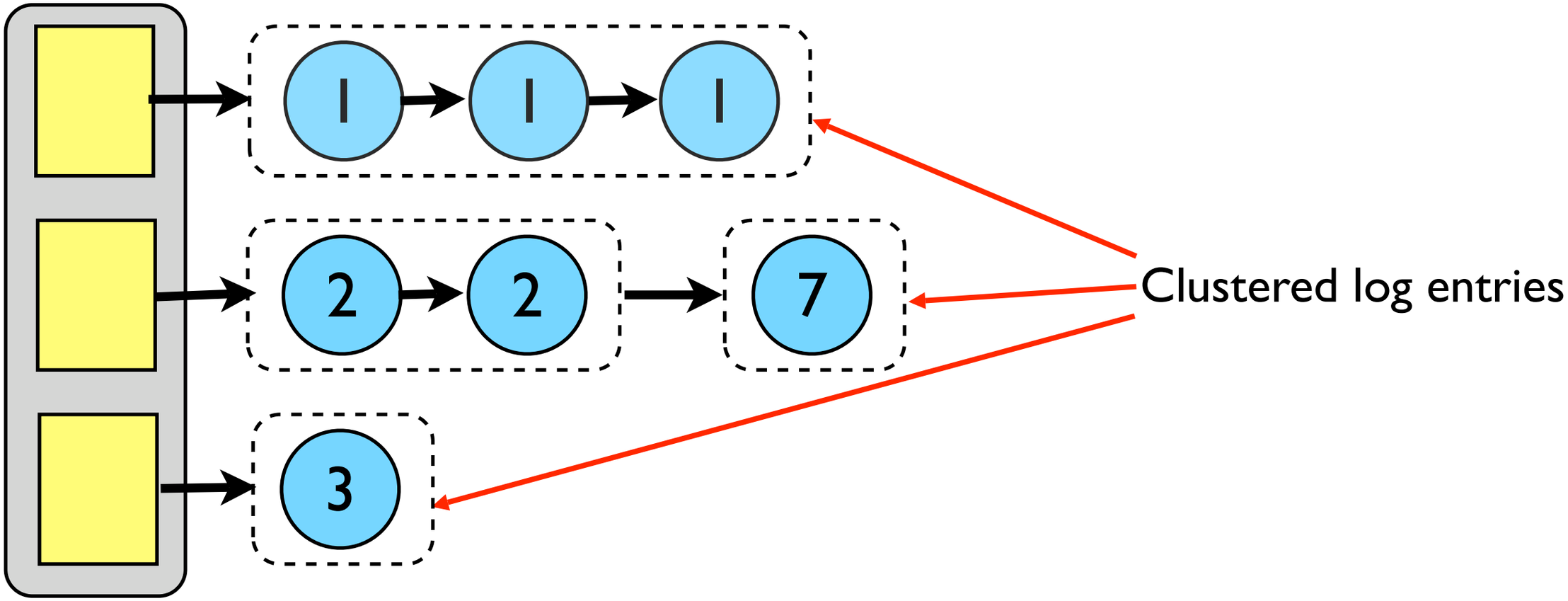
Index	State
<ID1>	S(ID1)
<ID2>	S(ID2)
•••	•••
<IDk>	S(IDk)

inode number

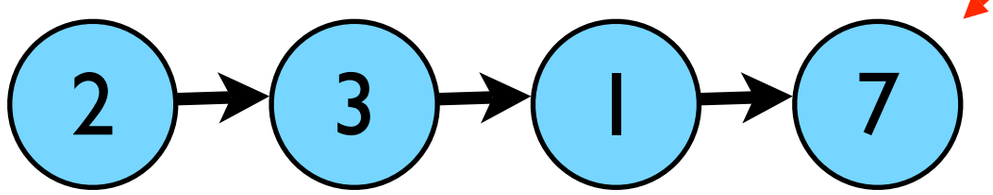
inode state

Consistency Checking

Transaction table (constructed from log)



Pending inode List



Consistency Checking Algorithm

- Initialize new log and state table
- Insert entries into transaction table and pending list
- For each inode on the pending list
  - If entry exists in "live" state table
    - Get next inode
  - If entry does not exist in the "live" state table
    - Fetch inode state from the "old" state table
    - Replay all ops in the transaction table
    - Compare replayed inode to "live" inode
  - Inconsistency if replay does not match "live" inode
- Requires O(1) lookup and replaying operations
- Block checks on NVRAM

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Prototype Implementation

- Implemented in LiFS
- Implemented protected regions in MRAM allocator
  - Required additional calls in the interface
  - mprotect
  - EVENODD
- Logged metadata operations in LiFS calls
  - All except extents and xattrs
- Implemented On-Line Consistency Checker
  - Currently outside of LiFS, but can read LiFS log
  - Currently builds structures outside of protected area
  - Persistent structures can be stored in protected area

Prototype Performance

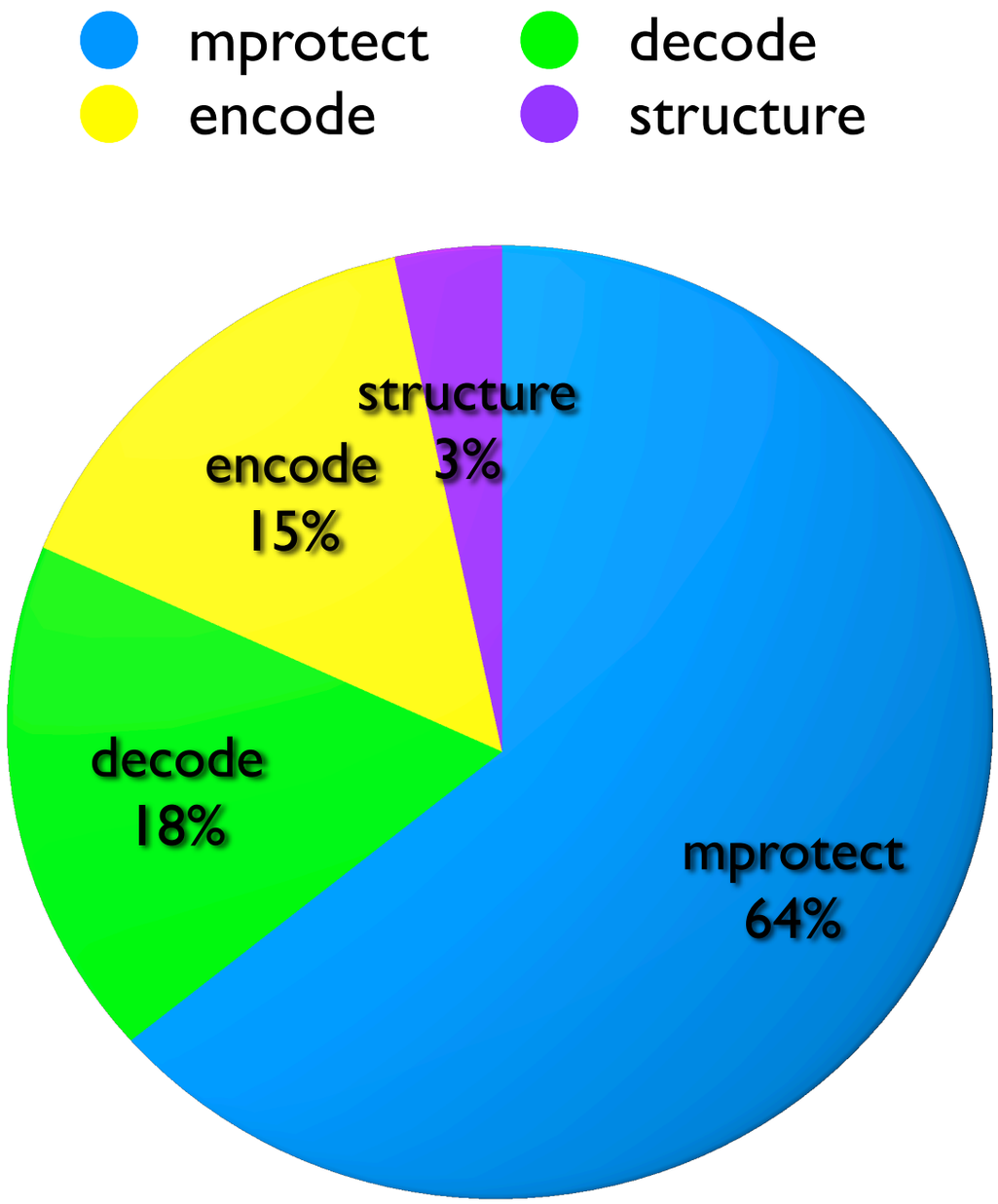
- Setup
  - 200 MB protected "MRAM" region
  - LiFS running through FUSE
  - EVENODD(96,64) and EVENODD(288,256)
- Fault Tolerance
  - Inject faults into protected region
  - Aggressively spawn threads that illegally write to region
  - Inject faults while performing valid writes to the region
- Raw write performance
  - Gives overhead for each prototype component
- File system write performance
  - Use a metadata write-centric workload
- Consistency Check Latency
  - Use same write-centric workload

Performance: Fault Tolerance

- Targeted entire 200 MB region
  - Performed 250,000 16-byte writes
  - Injected invalid writes while running workload
- Roughly 10,000 invalid writes were injected
  - 180-237 injected writes escaped page protection
  - 89-94% of these are caught by the EVENODD
  - Why not 100%?
    - Injected writes over-written by valid writes

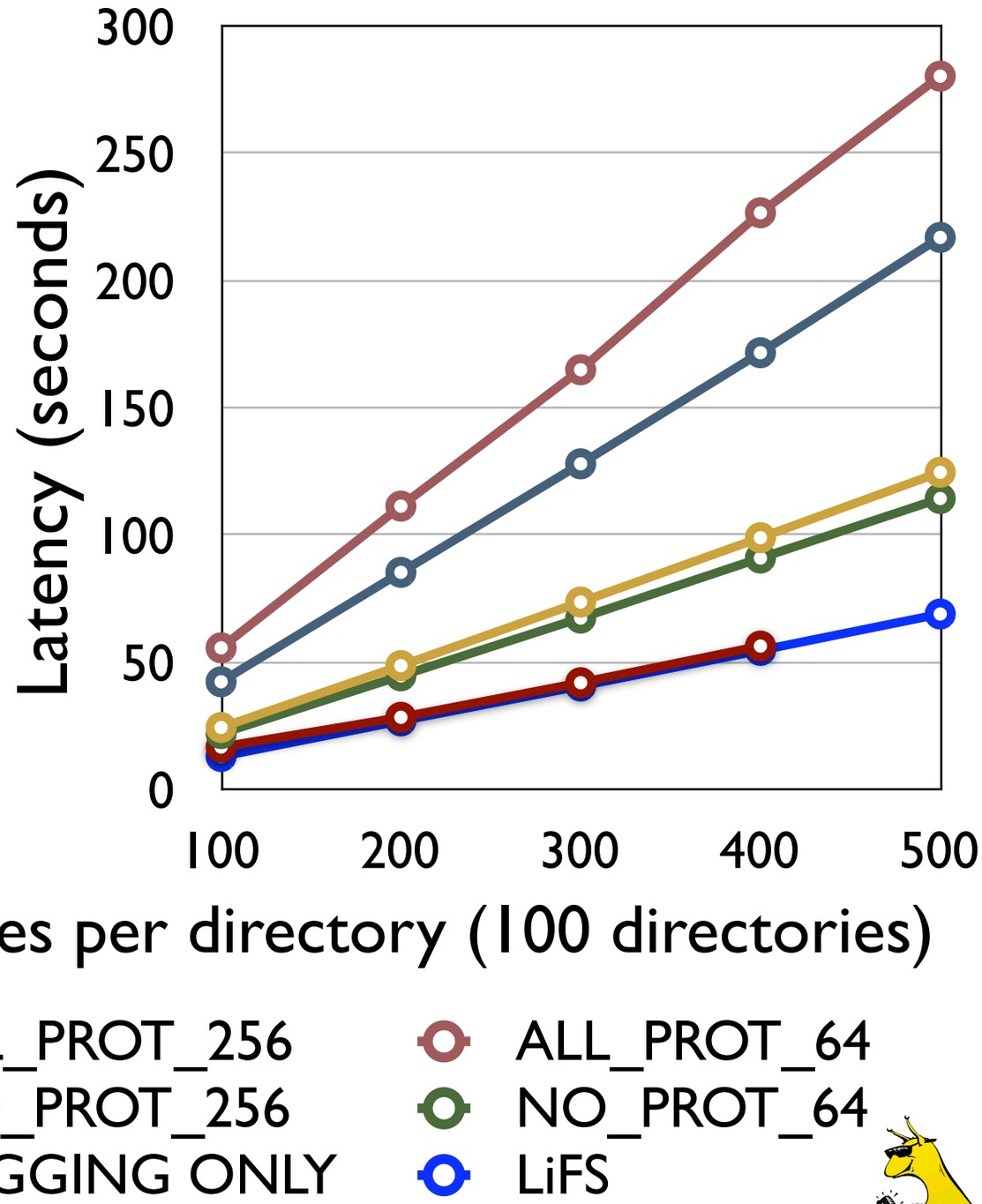
Performance: Raw Writes

- Most of the time is spent in mprotect
  - Mprotect: system call to protect memory
- Takes roughly 3 seconds to perform 250,000 writes
  - "Block" writes: small writes coalesced
- Without mprotect the same workload takes 1 second



File System Performance with Consistency Checking

- Create 100 directories
- Write 100-500 files to each directory
- Create links for each file
- Perm changes to file metadata
- Tests run with
  - Full protection
  - No mprotect
  - Only logging
  - Vanilla LiFS



Performance: On-Line Check

- Generated a log in LiFS
  - Same as latency workload (100 dirs/100-500 files)
  - Created 120,500–2.1 million operations
- Ran consistency checker outside of LiFS
  - Latency from less than 1 to 5.5 seconds

Related Work

- Queryable file systems
  - Expressive queries
  - Links don't have attributes (only files)
  - Advanced commercial file systems
    - Spotlight (Apple)
    - ZFS (Sun)
    - WinFS (eventually…)
  - Somewhat slow: information on disk
- In-memory file systems
  - Lack advanced file system features (links, searching)
  - No compression
  - Often treat memory as a block device (flash RAM)
  - Database research on utilizing persistent memory
- The Semantic Web

Future Work

- Push LiFS with these mechanisms into the kernel
- Distributed metadata using LiFS-based models
- RAID algorithms on multiple banks of MRAM
- Explore different approaches to data structures and compression
- Coding
  - Incorporate logging code for extents and x-attrs
  - Integrate the consistency checker into LiFS
  - Experiment with other ECCs
  - Allow communication between the MRAM-level mechanisms and the consistency checker

Conclusions

- MRAM promises big improvements for file systems
  - Richer metadata
  - Higher performance
  - Lower space requirements
  - Higher reliability
- Linking file system provides functionality currently unavailable
- Compression ensures that the metadata fits in MRAM
- Error correction and online consistency checking keep the metadata safe

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Questions?

- Thanks to our sponsors:
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  - SSRC industrial sponsors
  - LANL

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- http://www.ssrc.ucsc.edu/proj/scm.html